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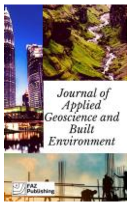

Quick Undrained Shear Strength Test comparison on London Clay

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Abstract: Shear strength of a soil is required to overcome problems involving earth pressure, bearing capacity of foundation, landslide, subsidence and the stability of slopes in cut or fills. London clay has a complex natural formation which also contributed problems to the researchers, developer's engineers and contractors in construction and infrastructural development. most researchers conducted experiment and investigation on shear strength of London clay using direct shear box test and simple shear test but only a few discovered the behaviour of it under quick undrained shear condition. The aim of this paper is to determine unconsolidated undrained shear strength properties of a remoulded London clay specimen for comparison purposes. four different soil specimen were obtained from four trial test boreholes at a depth in the range of 14-23m. Macroscale analysis was carried out including Atterberg limits, moisture content test and determination of shear strength parameters through triaxial compression testing. The result revealed that the natural water content, liquid limit and plastic limit has a mean value of 25.52, 69.5 and 23.81%. However, the sample has an apparent cohesion and internal angle of resistance are in the range of 149.3- 763.92kN/m^2 and 0 – 16^{o}c respectively. The average apparent cohesion and the plasticity values of the sample are very high and it is an indication that a good correlation exists between the two values. There is no increment in moisture content level throughout the test, this is an indication that the specimen was properly sealed with the membrane during the testing. The triaxial compression results have shown that the stress failure envelopes are not horizontal, and for this reason the average cohesion is taken with a zero angle of shearing resistance. Correlation between the apparent cohesion and that of the liquid limit and moisture content was carried out and the results have yielded a very good correlation except the one from borehole depth 17 m, this could probably be attributed to the lithology of the London clay.

Keywords: *Apparent cohesion, Clay, failure-envelopes, triaxial compression, Shear strength*

1. Introduction

Clay, a small soil particle less than 0.002 mm in size, existing naturally on the earth surface and comprising mainly of hydrous alumina-silicates having large interlayer spaces and in addition to some weathered rock materials [1.]. Clay has a characteristic to exhibit plasticity through an inconstant range of water content, that can solidify when dried [1,2]. Diverse types of clays, as well as clay minerals, perform an essential function in other parts of environment, for instance, it has been used as an active physiochemical adsorbent material in the removal of contaminants from aqueous solutions [3, 4,5]. Moreover, in the natural state it presents some challenges in engineering constructions especially foundations which emphasizes for serious investigations for safety and sustainability [.6].

The major constituent of London clay is poorly laminated, grey-brown or blue-grey, slightly calcareous, silty to very silty clay, clayey silt and sometimes silt, with some layers of sandy clay. Thin courses of carbonate concretion are common in London clay. Pockets of sand and thin beds of shells are found in it, which usually increase towards the base and the top of the formation. Flatbeds of black rounded flint gravel occur at the bottom, and at some other levels. (BGS, n.d.). Thin courses of carbonate concretion are common in London clay.

Similarly [7] describes it as ‘’greyish brown fissured silty clay of high plasticity and very high strength. Clay minerals are grouped into Kaoline, Illite and Montmorillonite groups. In all problems involving earth pressures, bearing capacity of foundations, landslides, and the stability of slopes in cuts or fills, the essential ingredient for a successful solution is a proper evaluation of the shear strength of the soil or soils involved [7, 8, 9] argued that the stratification and classification tests of London clay have yielded a good correlation. It was further outlined in the paper that material properties of London clay vary in each geological subdivision across central London; ‘’for engineering purposes, a categorisation based on the Atterberg limits of the materials would be preferred’’.

London clay is of considerable importance, as being the soil on which Bridges and many large buildings are founded. Also, the greater part of the tube railways are driven on it [10,11] Attention is more focused on clay because of its uniqueness. Some of the unique properties of clay include plastic behaviour when wet, volumetric changes, low permeability and swelling

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behaviour [12,13,14] Due to non-linear stress-strain response of London clay, it is essential in investigating the displacements induced by geotechnical construction [15, 16,] The investigation into the mechanical anisotropy of London clay has long been considered important in geotechnical engineering. For instance [17], found that the principal stress axis rotation occurs in soft clays under embankment loading, and highlighted the need for understanding the shear strength of natural London clay. [18] argued that London clay covers a large area, for this reason, the 1964 Rankine has focused on the investigation of the shear strengths of the clay. One of the major problem as far as construction is concern, is the possibility of subsidence where a structure has been erected on clay. This is one of the big challenges in southern England in the late 1970s and 1980s during the hot summer's period. Shrinkage of the clay occurred in the hot summer, which in turn resulted in the collapse, subside, and/or settlement of the buildings. The shrinkage and swelling behaviour of London clay formation due to volume change has resulted in foundation damage worth £500 million in 1991 [19-22].

2. Methodology

The quantitative research method was used for this research. Undrained unconsolidated shear strength test was conducted on the London clay. The undisturbed samples from the local construction firms were brought to the laboratory for the analysis. For the triaxial test, the specimens were subjected to a specified confining pressure and then the principal stress difference was applied immediately. There was no drainage /consolidation at any stage of the test. The test procedure was standardised in BS1377, part 7: 1990 (UK), CEN ISO/TS 17892-8 (Europe) and ASTM D2850 (US) [6]. The procedures in Clauses 3.2.3 and 7.2 of BS 1377: part 2: 1990.[23] was used in determining the moisture content in this study.

3. Result and discussion

3.1 Triaxial compression test

Unconsolidated Undrained tests sometimes refer as quick tests were carried out on London clay using the triaxial machine. For this type of test, a set of an identical specimen is tested and the clay sample is fully saturated, the total stress envelopes or circles have equal radius, and the angle of shearing resistance (ϕ_u) gave a zero value [24]. However, in almost all the tests conducted in the four boreholes pit, unequal total stress envelopes were achieved. The average apparent cohesion and the plasticity values of the sample are very high and it is an indication that a good correlation exists between the two values. There is no increment in moisture content level throughout the test, and this is an indication that the specimen was properly sealed with the membrane during the testing.

3.2 Triaxial compression test results of a borehole (1) at 17 m depth

The apparent **cohesion** (C_u) and the angle of shearing resistance (ϕ_u) for three sets of triaxial compression tests of the 17 m borehole depths are 149.3 kPa and 16^0 respectively as shown in Figure 1. The soil may be partially saturated that is the reason for having a value for the angle of shearing resistance [6]. The deviator stress at the failure for the three sets of specimens (A, B & C) is 471.96 kN/m^2, 567.73 kN/m^2 and 697.05 kN/m^2 respectively. While the percentage strains at failure are 3.0%, 5.5% and 4.5%. The test results are summarized in table 1.

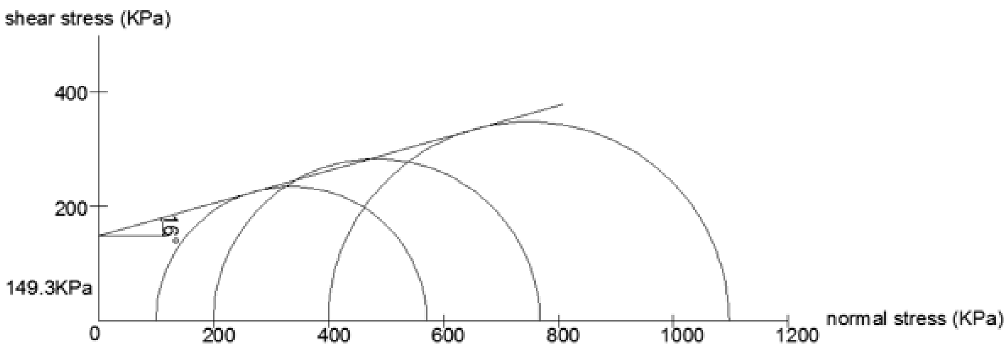

Figure 1: Summary of triaxial results for borehole (1) at 17 m depth

Table 1: Summary of triaxial results for borehole (1) at 14 m depth

Test no	Cell pressure (kN/m^2)	Deviator stress (kN/m^2)	Strain at failure (%)	Apparent cohesion (kN/m^2)	Angle of shearing resistance (ϕ_u) (degrees)	Moisture content: (%)
A	100	471.96	3	149.3	16	26.46
B	200	567.73	5.5	149.3	16	27.06
C	400	697.05	4.5	149.3	16	26.03

3.3 Triaxial compression test results for borehole 2 at 23 m depth

The 23 m depth borehole with a pit number 2 failed in terms of shear at an average apparent cohesion value of C_u = 551.44 kPa, and 0^0 of the angle of shearing resistance as illustrated in Figure 2. The factors for not having an equal radius of stress circle may be due to the existing natural fissure in the London clay sample, and also due to weathering which may not be constant at every point in the sample [25]. The deviator stress values at the failure range from 966.18 to 1224.57 kN/m^2 which correspond to 5-7 % of strain at failure and the moisture contents for the set of triaxial compression tests range between 21.26- 23.01 % as shown in table 2.

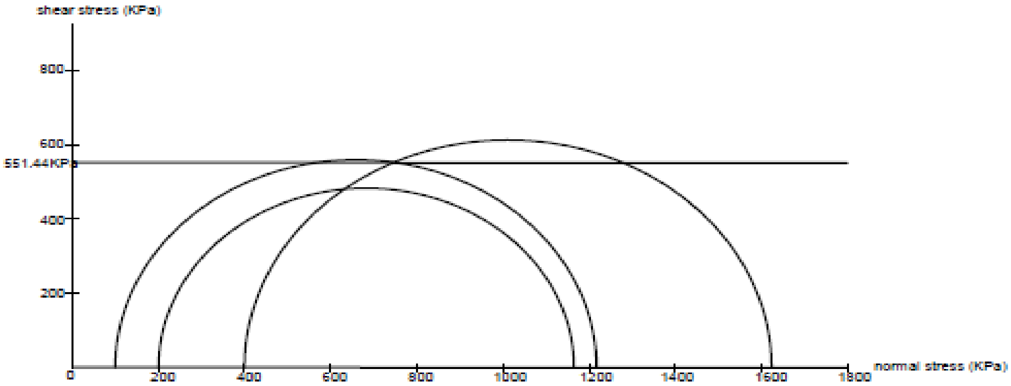

Figure 2: Summary of triaxial results for Borehole 2 at 23m depth

Table 2: Summary of triaxial results for borehole 2 at 23 m depth

Test no	Cell pressure (kN/m^2)	Deviator stress (kN/m^2)	Strain at failure (%)	Apparent cohesion (kN/m^2)	Angle of shearing resistance (ϕ_u) (degrees)	Moisture content: (%)
A	100	1117.89	5.5	551.44	0	21.92
B	200	966.18	5.0	551.44	0	21.26
C	400	1224.57	7.0	551.44	0	23.01

3.4 Triaxial compression test results of borehole (3) at 14 m depth

The borehole number 3 at the depth of 14 m, has an average cohesion value of 763.92 kpa with a zero 0^0 of the angle of shearing resistance as shown in Figure 3 [26]. The natural moisture content of the sample was 26.21%, whereas, for the test specimens, A and B are 20.51% and 21.82% respectively as shown in table 3. The loss of the moisture content occurred during the sample preparation and after that, the sample was kept for a couple of days before it was tested. The liquid limit of the clay specimen was 75% which means it has very high plasticity (BS 1377: 2: 1990). Since it has very high plasticity, then the clay soil is overconsolidated and for that reason it may have high apparent cohesion. A deviator stress values of 1883.93kn/m^2 and 1671.68 kN/m^2 with a corresponding percentage strains of 7% and 10% were recorded against test specimens A and B respectively. The details for the test results is summarized in table 3.

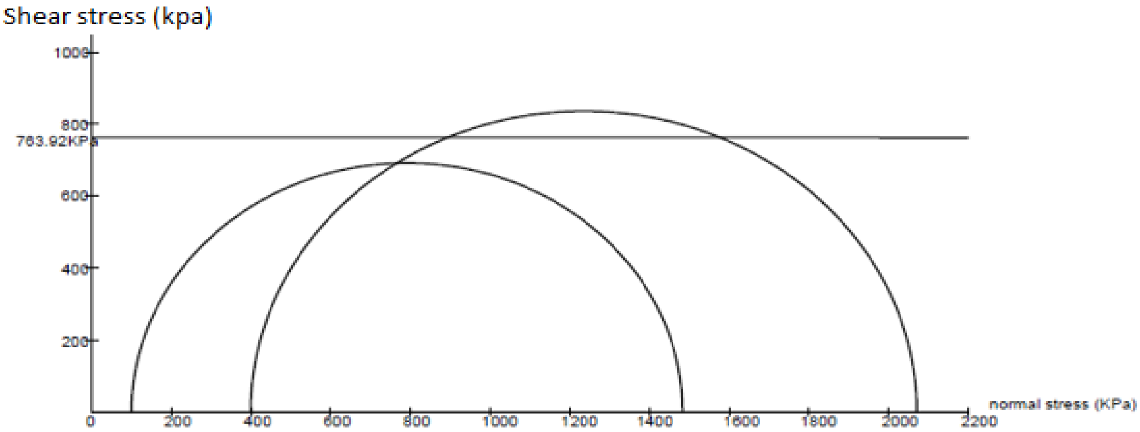

Figure 3: Triaxial compression test results of Borehole (3) at 14 m depth

Table 3: Summary of triaxial results for borehole (3) at 14 m depth

Test no	Cell pressure (kN/m^2)	Deviator stress (kN/m^2)	Strain at failure (%)	Average apparent cohesion (kN/m^2)	Angle of shearing resistance (ϕ_u) (degrees)	Moisture content: (%)
A	100	1383.92	7	763.92	0	20.51
B	400	1671.68	10	763.92	0	21.82

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3.5 Triaxial compression test results for borehole (4) at 23 m depth

The average apparent cohesion value of the sample specimen c_u = 335.56 KPa and the angle of shear strength is zero (ϕ_u= 0), the pore water is not affected with cavitation as a result of large value of negative pressure [26]. It is also possible that the envelope of the specimen in test B as shown in Figure 4 is low because the sample exists in slipped areas that had already sheared [27]. Specimen B has the lowest value of deviator stress (499.16 kN/m^2) at failure which corresponds to 4.5% value of strain at failure. While the highest value of the deviator stress (783.28 kN/m^2) at failure corresponded with 6% of strain at failure. Specimen C has 73.94 kN/m^2 value of deviator stress at failure which is in correspondence with 8% strain at failure as summarized in table 4.

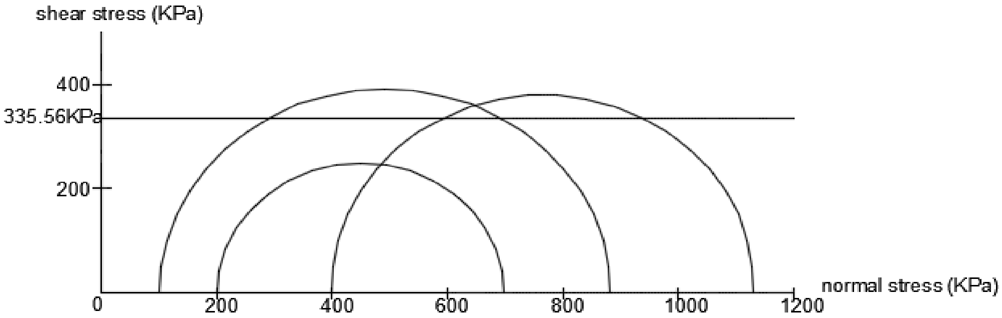

Figure 4: Summary of triaxial results for Borehole 5 at 23m depth

Table 4: Summary of triaxial results for borehole 5 at 23 m depth

Test no	Cell pressure (kN/m^2)	Deviator stress (kN/m^2)	Strain at failure (%)	Apparent cohesion (kN/m^2)	Angle of shearing resistance (ϕ_u) (degrees)	Moisture content: (%)
A	100	783.28	6	335.56	0	21.97
B	200	499.16	4.5	335.56	0	23.64
C	400	730.94	8	335.56	0	23.87

3.6 Atterbag Limit and Moisture Content

The mean liquid limit, plastic limit and natural moisture content conducted in the research are 69.5, 23.81 and 25.52% respectively, which are tabulated in table 5. [28] found that the liquid limit, plastic limit and moisture content variations over the entire site was recorded with a total range of values: 60 to 96 %; 21.4 to 32.4 %; and 24.5 to 28.7 % respectively. These values give a good correlation with the values obtained from the depth of the borehole in the tests conducted.

Table 5: Index properties of London clay

Property	Mean Value	Total range
Natural water content: percent of dry weight: (%)	25.52	24.96-26.41
Liquid limit: percent of dry weight: (%)	69.5	57-75
Plastic limit: percent of dry weight: (%)	23.81	21.02-30.04

The average penetrations for the samples range between 11.1 to 27.25 mm. The highest liquid limit recorded was 75% which correspond to the depths of 14 m and 17 m respectively. While the lowest liquid limit of 59% is in correspondence with the borehole at the depth of 23 m (borehole no 3), which is summarized in table 6. The soil sample can be classified as clay with very high plasticity with the exception of depth 23 m (BH 3), which is having high plasticity. The lithology of the sediments has a great impact on the variations of the Atterbag limits and moisture contents properties of the samples. The correlation of the average moisture contents of the borehole depths investigated lies within a comparatively small range, with the highest value (26.21%) recorded at 14 m. The lowest value (24.96%) corresponded to borehole no 3 at a depth of 23 m [29]. A correlation of average moisture content and liquid limit between boreholes of the same depth (23 m), and different borehole locations are carried out. A variation between the two results has been noticed as shown in table 5. This is evidence that geotechnical properties of the soil irrespective of the depth are unique for every location.

Table 6: Index properties and average moisture contents of London clay

Borehole no	Borehole depth: m	Average Moisture content: %	Liquid limit: %	Plastic limit: %	Plasticity index
5	14	26.21	75	23	52
2	17	25.12	75	30.04	44.96
2	23	25.58	67	21.16	35.98
5	23	24.96	59	21.02	49.85

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3.7 Correlation between apparent cohesion and liquid limit results.

The correlation between the apparent cohesion and liquid limit results (see table 7) have been carried out as shown in Figure 5. A good correlation was found in all the sample depths except borehole at 17 m depth. for this reason, borehole (3) at the depth of 14 m with apparent cohesion of 763.92 kN/m^2 and that of borehole (1) at depth of 17 m with apparent cohesion of 149.3 kN/m^2, both having the same moisture content of 75% are compared.

Table 7. correlation between the apparent cohesion and liquid limit

Borehole No.	Liquid Limit (%)	Apparent Cohesion (kN/m^2)
1	75	149.30
2	67	551.44
3	75	763.92
4	59	335.56

The discrepancy between the two values is due to the lithology of the London clay. The linearity of the graph proved that all the three specimens are overconsolidated London clay which has started drying up. Table 7: liquid limit and apparent cohesion values.

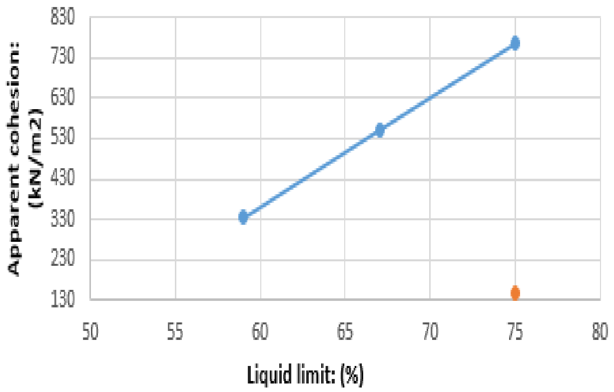

Figure 5: correlation between apparent cohesion and liquid limit

4.0 Conclusions and Recommendations

The triaxial compression results have shown that the stress failure envelopes are not horizontal, and for this reason, the average cohesion value is taken, and zero angle of shearing resistance was recorded. Correlation between the apparent cohesion and that of the liquid limit and moisture content was carried out and the results have yielded a very good correlation except the one from borehole depth 17 m. The lithology of the clay sample has shown that the borehole at 17 m depth is partially saturated, and that is why angle of shearing resistance is not zero and it has the lowest apparent cohesion value, while the other borehole depths are overconsolidated, which have started drying up.

The linear equation of strength y = 26.772x-1243.5 in terms of liquid limit and y = 342.67x-8216.4 in terms of moisture content were established. The undrained shear strength parameters use in bearing capacity, slope stability calculations and foundation related problems are found. The overconsolidated clay is very hard, with` undrained shear strength higher than (300 kN/m^2) and for the partially saturated is very stiff, with 149.3 kN/m^2 undrained shear strength value.

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